PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
H02K 19/06, 15/14

A1

(11) International Publication Number: WO 96/42132

(43) International Publication Date: 27 December 1996 (27.12.96)

(21) International Application Number: PCT/US96/06128

(22) International Filing Date: 7 May 1996 (07.05.96)

(30) Priority Data:
60/000,129 12 June 1995 (12.06.95) US

(71) Applicant *(for all designated States except US)*: ROSEN MOTORS, L.P. [US/US]; 6430 Independence Avenue, Woodland Hills, CA 91367 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: ROSEN, Harold, A. [US/US]; 14629 Hilltree Road, Santa Monica, CA 90402 (US). HUDSPETH, Thomas [US/US]; 6856 Wildlife Road, Malibu, CA 90256 (US). STAHL, David, A. [US/US]; 2409 Rutland Place, Thousand Oaks, CA 91362 (US). BAKHOLDIN, Daniel [US/US]; 18920 Felbridge Street, Canyon Count, CA 91351 (US).

(74) Agent: POWELL, Raymond, H., J.; P.O. Box 30269, Alexandria, VA 22310-0269 (US).

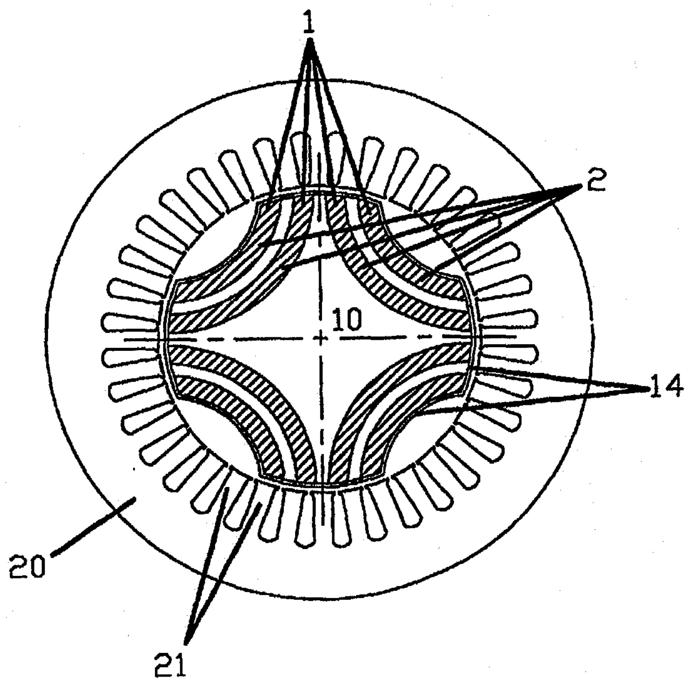
(81) Designated States: AL, AM, AT, AU, AZ, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, TJ, TM, TR, TT, UA, UG, US, UZ, VN, ARIPO patent (KE, LS, MW, SD, SZ, UG), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.

(54) Title: HIGH SPEED SYNCHRONOUS RELUCTANCE MOTOR-GENERATOR

(57) Abstract

A synchronous reluctance motor-generator exhibiting low eddy current and tooth harmonic losses, high bending stiffness and high radial strength, which can be manufactured at low cost, includes a stator and a conductively shielded solid rotor. The rotor for the synchronous reluctance machine is characterized as including at least one pair of magnetic material elements disposed at opposing ends of a line segment which line segment intersects the spin axis of the rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis, wherein the outer surface of the rotor, at least in the vicinity of the magnetic material elements, is covered with a layer of non-magnetic conducting material. A method for manufacturing a shielded solid rotor for a synchronous reluctance motor-generator and a clamping jig suitable for use with this method are also described.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgystan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic			SE	Sweden
CG	Congo	KR	Republic of Korea	SG	Singapore
CH	Switzerland	KZ	Kazakhstan	SI	Slovenia
CI	Côte d'Ivoire	LI	Liechtenstein	SK	Slovakia
CM	Cameroon	LK	Sri Lanka	SN	Senegal
CN	China	LR	Liberia	SZ	Swaziland
CS	Czechoslovakia	LT	Lithuania	TD	Chad
CZ	Czech Republic	LU	Luxembourg	TG	Togo
DE	Germany	LV	Latvia	TJ	Tajikistan
DK	Denmark	MC	Monaco	TT	Trinidad and Tobago
EE	Estonia	MD	Republic of Moldova	UA	Ukraine
ES	Spain	MG	Madagascar	UG	Uganda
FI	Finland	ML	Mali	US	United States of America
FR	France	MN	Mongolia	UZ	Uzbekistan
GA	Gabon	MR	Mauritania	VN	Viet Nam

HIGH SPEED SYNCHRONOUS RELUCTANCE MOTOR-GENERATOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to synchronous reluctance motor–generators. More specifically, the present invention relates to the rotor design of a synchronous reluctance motor–generator providing high bending stiffness, high radial strength and low eddy–current and low hysteresis losses. It will be appreciated that these characteristics make a synchronous reluctance motor–generator employing such a rotor ideal for high speed applications.

2. Brief Discussion of Related Art

Synchronous reluctance machines controlled by variable frequency inverters offer advantages over induction motors and permanent magnet machines in a variety of applications. The lower rotor loss associated with a properly designed rotor can result in a higher efficiency than in a comparably sized induction machine, while the lower material cost as compared to a similarly rated permanent magnet machine can make it less costly than those machines. For high speed applications, however, in which high centrifugal forces and shaft dynamic considerations can create problems, no previously described designs of synchronous reluctance machines have proven satisfactory.

Synchronous reluctance machines are described in a paper entitled "Synchronous Reluctance Machines – A Viable Alternative for AC Drives" by T. A. Lipo, Electrical Machines and Power Systems, 1991, pp. 659–671, and in "Design of a Synchronous Reluctance Motor Drive" by T. J. E. Miller et al. in IEEE Transactions on Industry Applications, Vol. 27, No. 4, July/August 1991. The design of the rotor for such a machine is specifically addressed by Lipo and Matsuo in "Rotor Design Optimization of Synchronous Reluctance Machine," IEEE Transactions on Energy Conversion, Vol. 9, No. 2, June 1994, pp. 359–365. These papers describe configurations which lead to low rotor loss with an acceptable power factor. These designs, however, which feature axial laminations, would fly apart at high rotational speeds.

U.S. Patent No. 4,924,130 entitled "Reluctance Synchronous Electric Machine Having Intrinsic Phase Correction Means" describes, in passing, an arrange-

ment of alternating ferro–magnetic and non–ferromagnetic axial laminations to obtain the anisotropy of reluctance necessary in these machines.

SUMMARY OF THE INVENTION

The present invention was motivated by a desire to preserve the characteristics of previously described designs, while correcting the problems associated with high speed operation, for synchronous reluctance motor–generators.

The principal object of the present invention is to provide a synchronous reluctance machine that can be operated at high efficiency in high speed applications. According to one aspect of the invention, several high speed synchronous reluctance motor–generators advantageously can be used in automotive applications wherein shaft speeds exceeding 100,000 RPM and rotor surface speeds exceeding 300 meters per second may be encountered in flywheel motor–generator and turbo–generator applications, for example.

Another object of the present invention is to provide a synchronous reluctance machine having a rotor suitable for high operating speeds which can be manufactured at low cost.

Yet another object of the present invention is to provide a synchronous reluctance machine having a rotor which is high in efficiency and low in cost for moderate speed applications.

Still another object of the present invention is to provide a synchronous reluctance machine having a rotor which can be operated at high temperatures.

These and other objects, features and advantages according to the present invention are provided by a rotor for a synchronous reluctance motor–generator, the rotor being characterized in that the rotor includes at least one pair of magnetic material elements disposed at opposing ends of a line segment, which line segment intersects the spin axis of the rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis, wherein the outside surface of the rotor, at least in the vicinity of the magnetic material elements, is covered with a layer of non-magnetic conducting material. According to one aspect of the invention, the conducting material is copper. Alternatively, other conducting materials, e.g., silver, can be used in forming the outer conducting layer, i.e., the shield layer.

These and other objects, features and advantages according to the present invention are provided by a method for manufacturing a rotor for a synchronous reluctance motor–generator. The method includes steps for providing at least one pair of magnetic material elements, positioning the elements at opposing ends of a line segment, which line segment intersects the spin axis of the rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis, bonding the elements to the rotor, and coating the outside surface of the rotor, at least in the vicinity of the magnetic material elements, so as to form a layer of non-magnetic conducting material on the rotor. According to one aspect of the invention, a conducting material, e.g., copper or silver, can be formed into the conducting material layer by plating. Alternatively, the conducting materials can be formed into the conducting material layer by a process such as vapor deposition, cladding, brazing, casting, diffusion bonding or thermal spraying.

BRIEF DESCRIPTION OF THE DRAWINGS

The preferred embodiments are described with reference to the drawings wherein:

Fig. 1A illustrates a side view of a cylindrical rotor while Figs. 1B through 1D illustrate rotor cross sections for 2, 4 and 8 pole rotors, respectively;

Fig. 2, by showing a step-wise approximation for sinusoidal spacial distribution, is useful in understanding an air gap field excited by the stator for a typical synchronous reluctance machine;

Figs. 3A and 3B depict transversely and axially laminated rotor configurations, respectively, which can be used in a synchronous reluctance motor–generator;

Fig. 4 depicts an exemplary rotor with an integral conductive shield disposed within an exemplary stator of a synchronous reluctance motor–generator according to the present invention;

Fig. 5 is a chart comparing rotor loss for both an unshielded solid and conventional laminated rotors with that of the shielded solid rotor according to the present invention;

Figs. 6A and 6B are exemplary illustrations showing rotor components before and after bonding, respectively; and

Fig. 7 illustrates an example of a fixture which finds application in the bonding of rotor segments during manufacture of the shielded rotor for a synchronous reluctance motor–generator according to the method of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1A illustrates an exemplary rotor 10 while the rotor cross sections shown in Figs. 1B to 1D are typical of the current art for rotors of synchronous reluctance motor–generators. The alternation of magnetic material elements 1 and non–magnetic material elements 2 in the poles of the rotor 10 shown, for example, in Fig. 1C, provide the required anisotropy needed for torque production. For clarity, the magnetic material elements 1 are designated by shading. Moreover, while a variety of pole configurations is permitted, the description which follows treats the exemplary case of a four (4) pole rotor formed from 4N magnetic material elements and 4M non-magnetic material elements uniformly spaced about a cruciform rotor core 3. It will be noted that N is an integer greater than or equal to 1 while M is typically in the range of values between N-1 and N+1.

In synchronous reluctance machines, the magnetic field produced by the stator rotates in synchronism with the solid rotor 10, causing the field in the rotor to be substantially unvarying. Typical stator configurations are illustrated in the papers by T. J. E. Miller et al. and Lipo and Matsuo, which papers are discussed above and which papers are incorporated herein by reference for all purposes. It will be appreciated that the larger the volume ratio of non–magnetic to magnetic material, the better the power factor of the machine. However, it also should be noted that when this ratio becomes too large, the output torque of the motor-generator suffers.

It will also be appreciated that because the stator field is produced by a discreet arrangement of teeth, the desired sinusoidal spacial distribution of flux density can be approximated by the stepwise distribution shown in Fig. 2. As the rotor 10 rotates past stationary teeth 22 of stator 20, as illustrated, for example, in Fig. 4, the rotor 10 encounters flux variations at a frequency approximately equal to (N x RPM)/60, where N is the number of teeth 22 in stator 20, and RPM is the shaft speed in revolutions per minute. For an exemplary shaft

speed of 60,000 RPM in a machine having 36 teeth, this frequency, commonly referred to as the tooth harmonic, is 36 kHz. It will also be appreciated that in a well designed machine, the eddy currents caused by this high frequency flux variation are the primary cause of rotor loss.

In most electrical machines, losses due to eddy currents can be reduced to acceptable levels by using thin laminations, i.e., a plurality of lamination layers, to break up the conducting path. The usual lamination arrangement consists of thin transverse slices of the ferro-magnetic material. However, since the rotor 10 of the synchronous reluctance machine consists of alternating magnetic material elements 1 and non-magnetic material elements 2, or other suitable materials, as shown in, for example, Fig. 1C, the fabrication of transverse laminations becomes complex and expensive. As can be seen readily from Fig. 3A, each of the plates used in forming the laminated rotor are bimetallic plates. For this reason, axial laminations, such as those illustrated in Fig. 3B, are preferred in modern synchronous reluctance motor-generators.

Axially laminated rotors can be incorporated into synchronous reluctance motor-generators which perform well at relatively low shaft speeds. However, this type of rotor is difficult to design for high speed operation, primarily due to fact that the relatively low tensile strength of the interlaminar insulation cannot cope with the high centrifugal forces encountered by the rotor 10. In extreme cases, the rotor flies apart. While the transverse laminations illustrated in Fig. 3A do not have this problem, this type of rotor is often prohibitively expensive to manufacture, especially in the ultra-thin sections desired for reducing losses resulting from the high frequencies of the tooth harmonics.

As shown in Fig. 4, a relatively elegant and inexpensive solution to this dilemma is the use of a highly conductive coating on the exterior of an unlaminated solid rotor, thereby producing a shielded solid rotor. Eddy currents produced in this conducting shield layer 14 create a radial magnetic field which opposes the radial component of the inter-tooth flux, thereby preventing the inter-tooth flux from entering the lossier ferrous material sections of the rotor. Thus, even though the eddy currents in the conducting shield layer 14 produce losses, which losses are shown in Fig. 5, these losses are lower than those produced by

either an unshielded solid rotor or a transverse laminated rotor in the tooth harmonic frequency range of interest, *e.g.,* 20-40 kHz.

While still discussing Fig. 4, it should be noted that for operation in a vacuum, *i.e.,* the normal operating environment of a high speed flywheel assembly, windage loss does not exist. Therefore, the outer surface need not be a smooth circular cylinder, thus permitting the non–magnetic material between the poles of rotor 10 to be eliminated.

Results of small scale tests comparing the temperature rise rates for an unshielded solid rotor, an unshielded laminated rotor and a shielded solid rotor 10 according to the present invention are denoted by Curves A through C, respectively, in Fig. 5 for various tooth harmonic frequencies. The temperature rise rates are used since the temperature rise rates are directly proportional to the rotor loss. The tooth excitation used to simulate tooth harmonic excitation were equivalent to the full range of operating speeds expected to be encountered by a rotor incorporated into a flywheel motor generator. The solid rotors tested were magnetic steel cylinders and laminated rotors were built up from 0.35 millimeter thick laminations of magnetic steel; the shielded solid rotors tested were magnetic steel cylinders plated with a 0.5 millimeter thick layer of silver.

The effectiveness of the shield in reducing power loss results from its low resistance to the eddy currents. Since the eddy currents are confined to a thin layer near the surface approximately one skin depth in thickness, it is the resistivity characteristic of this layer that is important. This resistivity is proportional to the square root of the product of the electrical resistivity and the relative permeability, *e.g.,* relative with respect to the permeability of free space, of the material. Therefore, a low resistivity, low relative permeability (i.e., non-magnetic) material is required. Any non-magnetic metal used as a shield will be effective; low resistivity non-magnetic metals used as a shield will be more effective. The most effective configuration of the shielded solid rotor for reducing losses will satisfy the condition that the product of magnetic material's electrical resistivity and relative permeability >> the product of the non-magnetic material's electrical resistivity and relative permeability.

The Table immediately below provides a non-limiting list of non-magnetic

materials and their respective electrical resistivity ranges which are suitable for use as the conducting shield layer 14.

MATERIAL	ELECTRICAL RESISTIVITY	
	HIGH	LOW
Series 3000 Aluminum Alloys	4.2 $\mu\Omega$-cm	1.71 $\mu\Omega$-cm
Coppers, wrought	3.82 $\mu\Omega$-cm	2.8 $\mu\Omega$-cm
Series 1000 Aluminum Alloys	3.0 $\mu\Omega$-cm	-
Gold Plating	2.4 $\mu\Omega$-cm	-
Gold	2.19 $\mu\Omega$-cm	-
Silver Plating	1.6 $\mu\Omega$-cm	-
Silver	1.47 $\mu\Omega$-cm	-

Shielded solid rotors, which are suitable for a flywheel motor–generator capable of sustained rotational speeds in excess of 60,000 RPM, can be manufactured using one of the exemplary methods described immediately below.

First, the various magnetic and non-magnetic elements can be prepared using conventional fabrication techniques. In the exemplary case under discussion, the magnetic material 1' and non–magnetic material 2' used are 4130 alloy steel and Inconel 718, respectively, while the braze alloy 4 used is B Ni–2 nickel braze strip. The magnetic and non–magnetic materials 1' and 2' are machined to fit and then assembled as shown in Fig. 6A. This assembly advantageously can be restrained in a brazing fixture or jig 200, as shown in Fig. 7, and brazed. In view of the fact that forms 202 and associated bolts 206 are formed from materials with relatively low coefficients of thermal expansion, *e.g.*, $8.3 \times 10^{-6}/°F$, while spacers 204 are formed from a material having a relatively high coefficient of thermal expansion, *e.g.*, $9.6 \times 10^{-6}/°F$, fixture 200 creates symmetrical clamping forces. More importantly, these symmetrical clamping forces increase during the furnace brazing cycle, which is typically at temperatures in excess of 1950° F. Advantageously, the generated clamping forces eliminate voids in the braze joints. It will be appreciated that the corners of the forms 202 act as indexing positions with respect to the elements 1'. It will also be appreciated that the

arrangement of Fig. 7 is an exemplary configuration and that other configurations will occur to those of ordinary skill in the art.

After the brazing step is completed, the solid rotor piece thus formed is machined on its outside diameter and then coated with a non-magnetic conducting material, *e.g.,* silver, on all exterior surfaces to thereby form the shielded solid rotor 10 for the synchronous reluctance motor–generator according to the present invention. In an exemplary case, the conducting material is applied to the solid rotor by plating. It will be appreciated that other coating processes such as vapor deposition, cladding, brazing, casting and thermal spraying can also be employed.

Advantageously, shielded solid rotors can be manufactured by the general steps of casting, forming or machining precisely interlocking elements of magnetic and non–magnetic materials 1′ and 2′, bonding these elements to one another in an alternating layer pattern and then coating the majority of the solid rotor with a conducting material. It will be appreciated that the materials must be chosen to meet the magnetic, non–magnetic and strength requirements of the intended application. While an exemplary bonding process of brazing individual elements into a solid rotor was previously described, the solid rotor advantageously can be formed using a selected one of the processes including diffusion bonding, soldering, casting, forging, welding and explosive forming. Moreover, the solid rotor can also be formed using compacting, sintering and consolidating, *i.e.,* the so-called powder metallurgy processes. It will also be appreciated that the fabrication process chosen must be compatible with the materials used and be strong enough to sustain the stresses associated with the high spin speeds.

During the selected forming or bonding process, pressure advantageously may be applied to hold the alternating magnetic and non-magnetic materials 1′ and 2′ in place while preventing the formation of voids in the bond zone. After bonding, the solid rotor thus formed is subsequently machined and then coated or plated with a relatively low electrical resistivity coating on substantially all of the exposed exterior surface of the solid rotor, thus forming the shielded solid rotor.

WHAT IS CLAIMED IS:

1. A synchronous reluctance motor–generator comprising:

a stator; and

a conductively shielded solid rotor.

2. The synchronous reluctance motor–generator recited in claim 1, wherein the shielded solid rotor is un-laminated.

3. The synchronous reluctance motor–generator as recited in claim 1, wherein said conductively shielded solid rotor comprises:

a solid rotor including a plurality of magnetic material elements disposed around the spin axis of said solid rotor; and

a layer of conducting material coating substantially the entire outer surface of said solid rotor, at least in the vicinity of said magnetic material elements,

wherein said magnetic material elements have a first electrical resistivity and a first relative permeability,

wherein said conducting material has a second electrical resistivity and a second relative permeability, and

wherein said magnetic material elements and said conducting material satisfy the condition that the product of said first electrical resistivity and said first relative permeability $>>$ the product of said second electrical resistivity and said second relative permeability.

4. The shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 3, wherein said conducting material is non-magnetic and has an electrical resistivity $\leq$ 5.0 microohm-cm.

5. A shielded solid rotor for a synchronous reluctance motor–generator, wherein said shielded solid rotor is characterized in that said shielded solid rotor includes at least one pair of magnetic material elements which elements are disposed at opposing ends of a line segment, which line segment intersects the spin axis of said rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis, wherein an outside surface of said shielded solid rotor, at least in the vicinity of said magnetic material elements, is covered with a layer of non-magnetic conducting material.

6. The shielded solid rotor for a synchronous reluctance motor–generator

as recited in claim 5, wherein said magnetic material elements have a first electrical resistivity and a first relative permeability, wherein said conducting material has a second electrical resistivity and a second relative permeability and wherein said magnetic material elements and said conducting material satisfy the condition that the product of said first electrical resistivity and said first relative permeability >> the product of said second electrical resistivity and said second relative permeability.

7. The shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 6, wherein said conducting material is copper.

8. The rotor for a synchronous reluctance motor–generator as recited in claim 6, wherein said conducting material is silver.

9. The shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 5, wherein said conducting material has an electrical resistivity ≤ 5.0 microohm-cm.

10. A method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator, said method comprising the steps of:

(a) providing a solid rotor including at least one pair of magnetic material elements at opposing ends of a line segment intersecting the spin axis of said solid rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis of said solid rotor;

(b) coating substantially all outside surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form a layer of non-magnetic conducting material on the rotor to thereby form a shielded solid rotor.

11. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) comprises the steps of:

(a)(i) providing said at least one pair of magnetic material elements and a rotor core;

(a)(ii) positioning said elements at opposing ends of a line segment intersecting the spin axis of said rotor core and which line segment is included in a plane disposed substantially perpendicular to the spin axis; and

(a)(iii) brazing all of said elements to said rotor core to thereby form said

solid rotor.

12. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) comprises the steps of:

(a)(i) providing a plurality of magnetic material elements and a cruciform rotor core;

(a)(ii) positioning pairs of said elements at opposing ends of respective line segments intersecting the spin axis of said cruciform rotor core and which line segments are included in respective planes disposed substantially perpendicular to and equidistantly spaced around the spin axis;

(a)(iii) clamping said elements in respective fixed positions with respect to said cruciform rotor core using a plurality of spacers having a relatively high coefficient of thermal expansion disposed around a jig having a relatively low coefficient of thermal expansion; and

(a)(iii) brazing all of said elements to said cruciform rotor core to thereby form said solid rotor.

13. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) comprises the step of plating substantially all outside surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, with copper to thereby form a shielded solid rotor.

14. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) comprises the step of plating substantially all outside surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, with silver to thereby form a shielded solid rotor.

15. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said magnetic material elements have a first electrical resistivity and a first relative permeability, wherein said conducting material has a second electrical resistivity and a second relative permeability and wherein said magnetic material elements and said conducting material satisfy the condition that the product of said first electrical resistivity and

said first relative permeability > > the product of said second electrical resistivity and said second relative permeability.

16. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) further comprises forming said solid rotor including at least one pair of magnetic material elements at opposing ends of a line segment intersecting the spin axis of said solid rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis of said solid rotor by a casting process.

17. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) further comprises forming said solid rotor including at least one pair of magnetic material elements at opposing ends of a line segment intersecting the spin axis of said solid rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis of said solid rotor by a diffusion bonding process.

18. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) further comprises forming said solid rotor including at least one pair of magnetic material elements at opposing ends of a line segment intersecting the spin axis of said solid rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis of said solid rotor by a powder metallurgy process.

19. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (a) further comprises forming said solid rotor including at least one pair of magnetic material elements at opposing ends of a line segment intersecting the spin axis of said solid rotor and which line segment is included in a plane disposed substantially perpendicular to the spin axis of said solid rotor by a process selected from a group consisting of forging, welding, thermal spraying and explosive forming.

20. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises plating substantially all outside surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said layer of said conducting material on the solid rotor to thereby form said shielded solid rotor.

21. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises vapor depositing said layer of said conducting material over substantially all outside surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said shielded solid rotor.

22. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises cladding over substantially all outer surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said layer of said conducting material on the solid rotor to thereby form said shielded solid rotor.

23. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises brazing said layer of said conducting material over substantially all outer surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said shielded solid rotor.

24. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises casting said layer of said conducting material over substantially all outer surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said shielded solid rotor.

25. The method for manufacturing a shielded solid rotor for a synchronous reluctance motor–generator as recited in claim 10, wherein said step (b) further comprises thermal spraying said layer of said conducting material over substantially all outer surfaces of said solid rotor, at least in the vicinity of said magnetic material elements, so as to form said shielded solid rotor.

26. A clamping apparatus for holding a plurality of elements including N magnetic material elements at fixed positions with respect to a non-uniform radius rotor core during manufacture of a solid rotor for a synchronous reluctance motor–generator, said clamping apparatus comprising:

at least one form member defining an area capable of accommodating the rotor core, said form member including N indexing positions and first and second ends, said form member having a first coefficient of thermal expansion;

an attaching element, operatively connected to said first and said second ends of said form member, capable of varying the separation between said first and said second ends, said attaching element having a second coefficient of thermal expansion; and

N spacers for connecting a selected indexing position of said form member with a corresponding one of said N elements, each of said N spacers having a third coefficient of thermal expansion,

wherein N is an integer greater than 1,

wherein said first and said second coefficients of thermal expansion are substantially equal to one another, and

wherein said third coefficient of thermal expansion is greater than that of said first and said second coefficients to thereby permit an increase in temperature during a process step to produce a resultant increase in clamping forces symmetrically applied to said N elements and said rotor core.

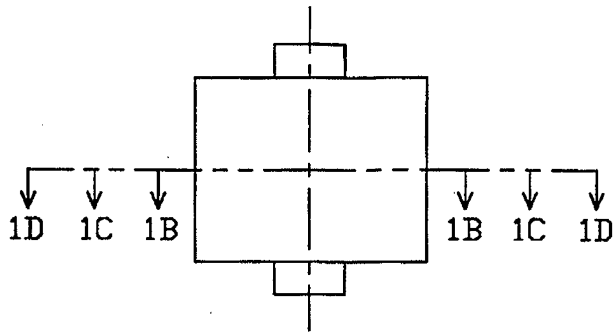


FIG. 1A

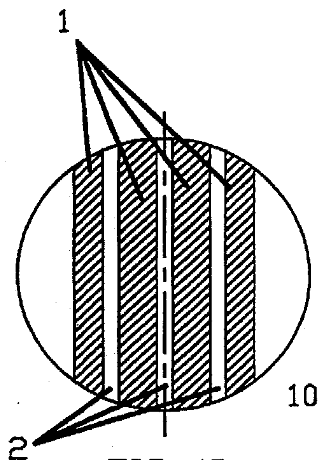


FIG. 1B

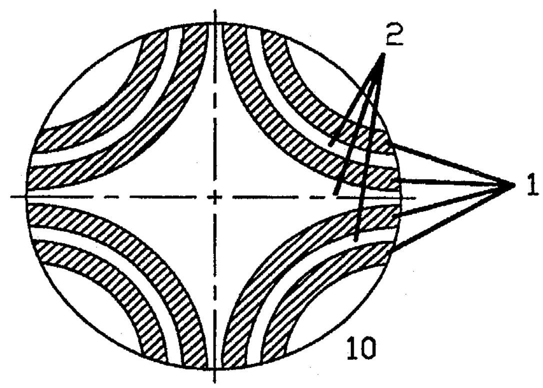


FIG. 1C

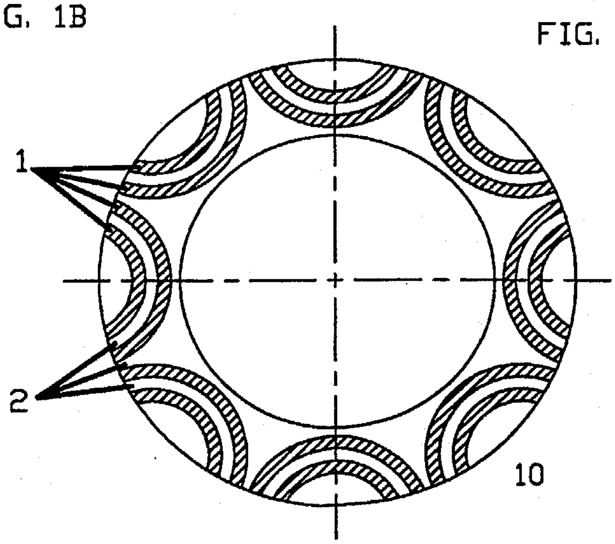


FIG. 1D

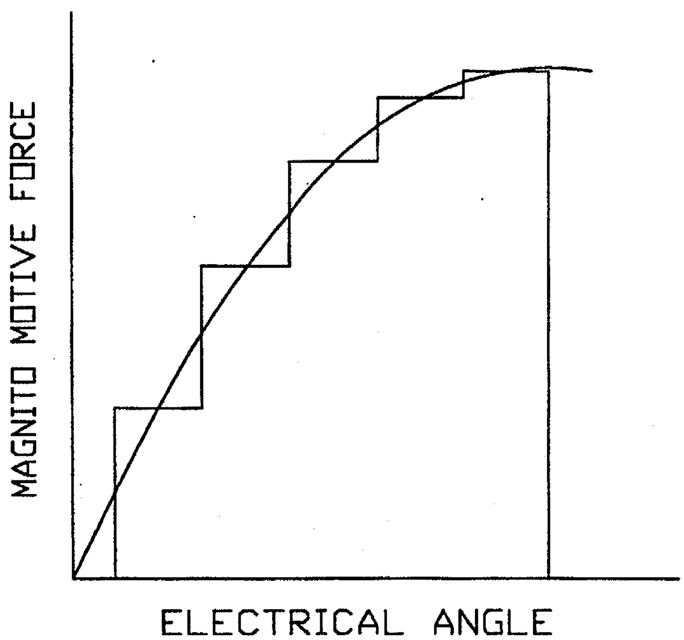


FIG. 2

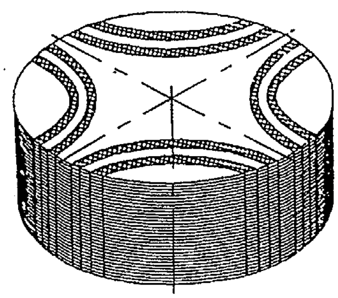


FIG. 3A

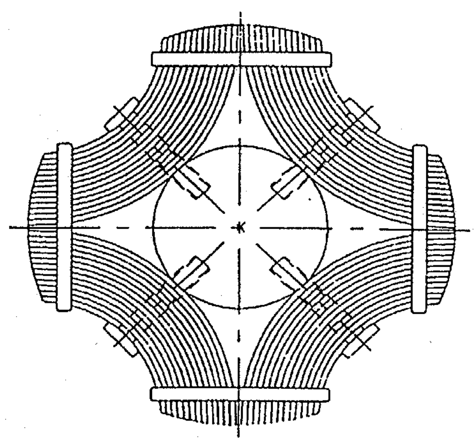


FIG. 3B

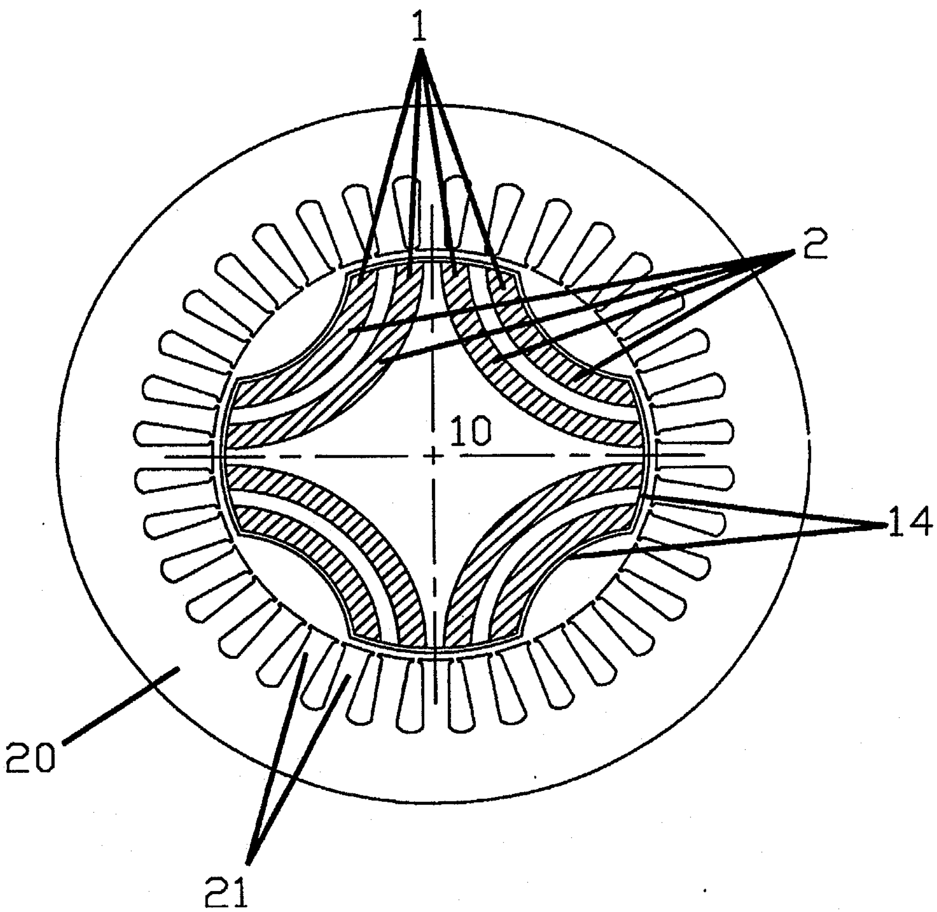
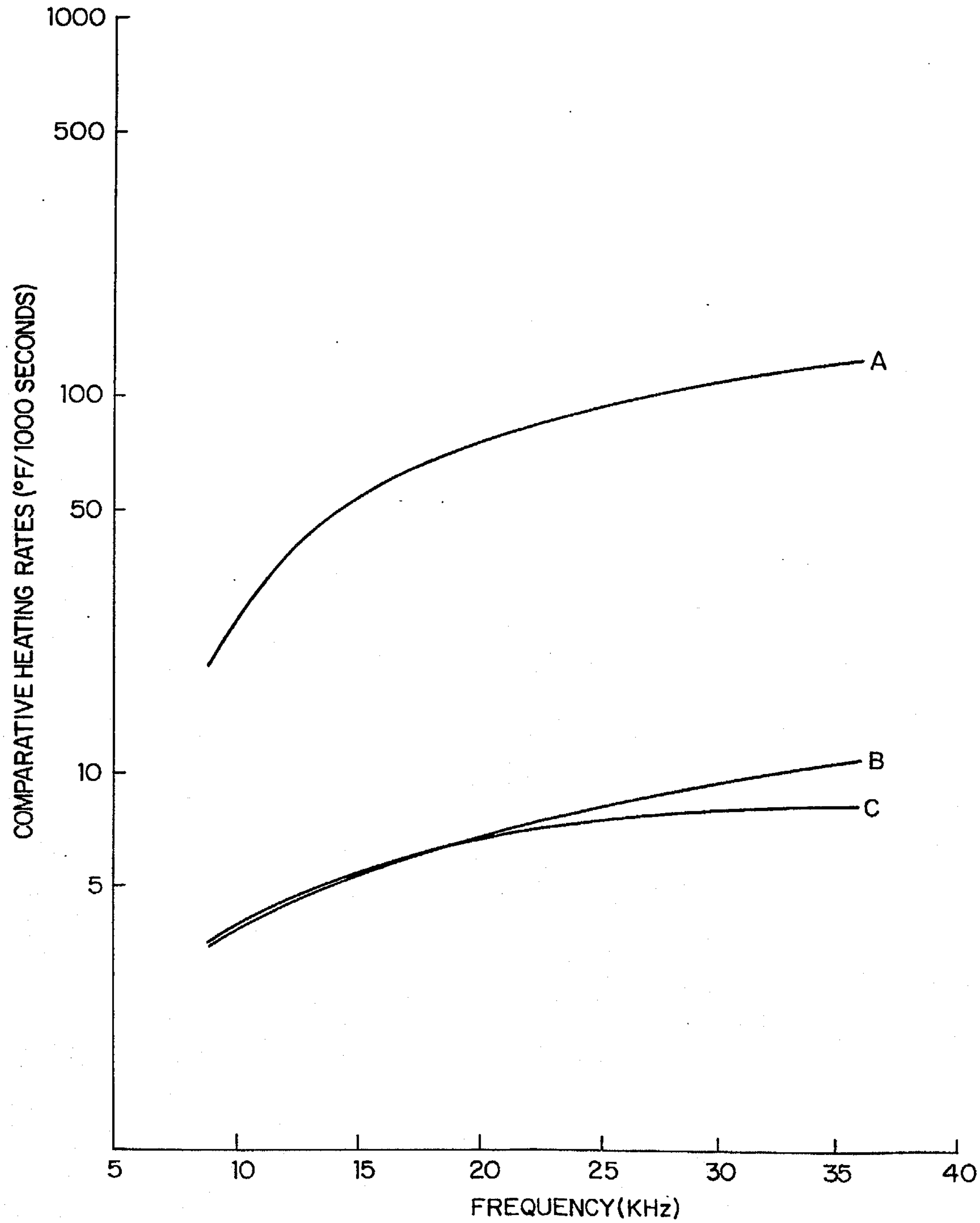


FIG. 4

FIG. 5


1000
500
100
50
10
5
COMPARATIVE HEATING RATES (°F/1000 SECONDS)
A
B
C
5
10
15
20
25
30
35
40
FREQUENCY(KHz)

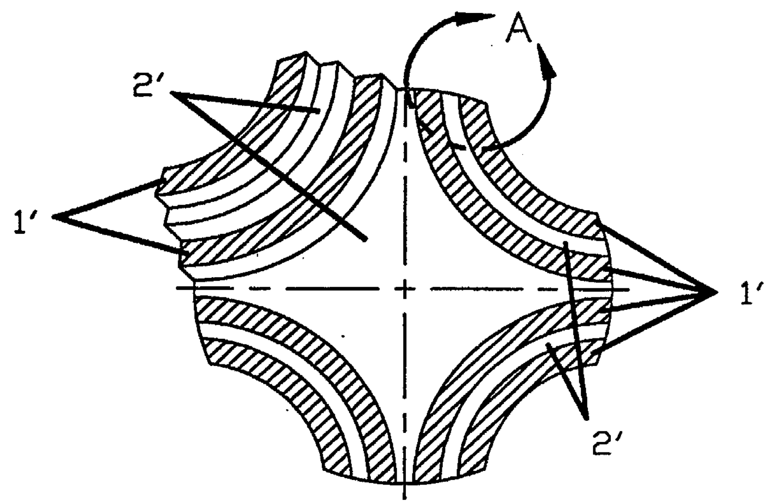
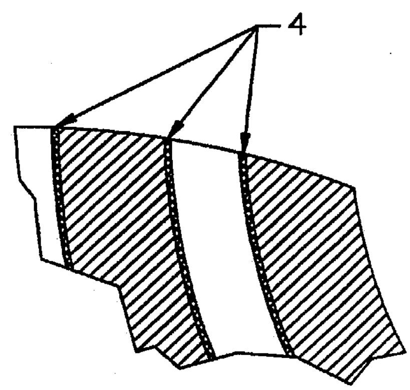


FIG. 6A



VIEW A

FIG. 6B

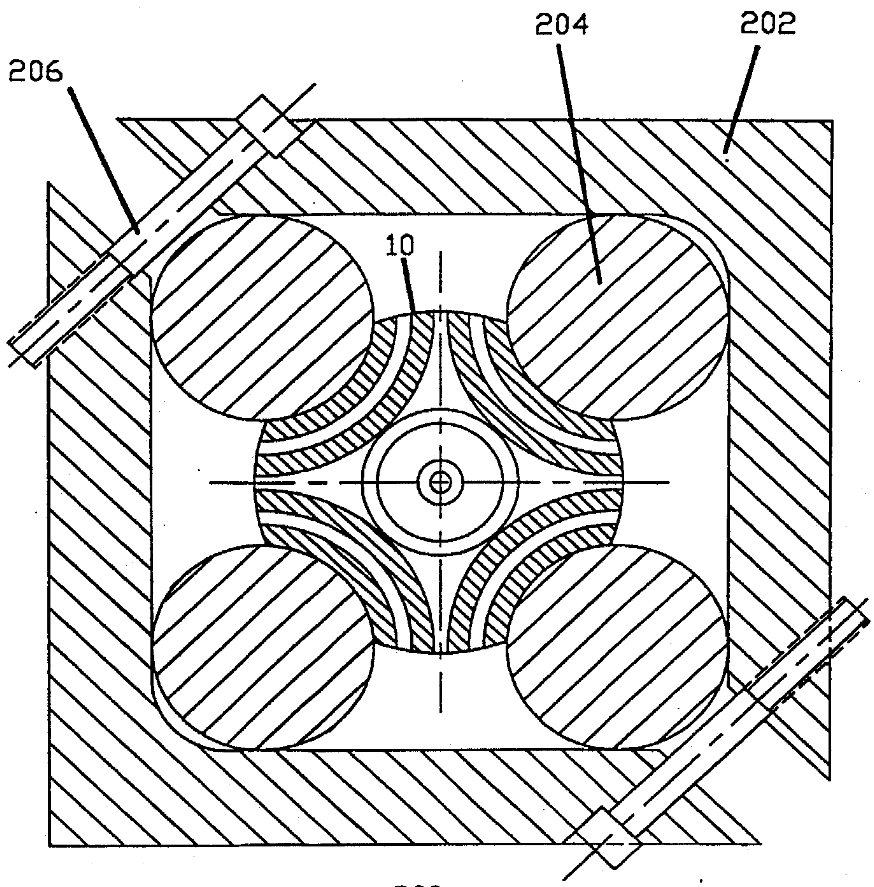


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/06128

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : HO2K 19/06, 15/14
US CL : 29/596,598; 310/168,261
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 29/596,598; 310/168,261,44,162,166,156

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y --- A	US, A, 4,888,513 (FRATTA) 19 December 1989, figs. 3 and 5-7	1 --- 2-25 --- 26
X --- Y --- A	US, A, 4,924,130 (FRATTA) 08 May 1990, Figs. 3,5 and 7.	1 --- 2-25 --- 26
Y --- A	US, A, 4,777,396 (ITO ET AL) 11 October 1988, col. 2, line 63 - col. 3, line 60	3-25 --- 26
Y	US, A, 4,395,711 (WARD) 26 July 1983, col. 3, lines 19-	7,8

[X] Further documents are listed in the continuation of Box C. [ ] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
18 JULY 1996	17 SEP 1996

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	for MICHAEL WALLACE
Facsimile No. (703) 305-3230	Telephone No. (703) 308-7478

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US96/06128

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 5,232,652 (BIANCO) 3 August 1993, col. 1, lines 60-63.	18
Y	US, A, 4,679,314 (LENZ ET AL) 14 July 1987, col. 1.	20,23 and 24
Y	US, A, 3,858,308 (PETERSON) 07 January 1975, col. 6, lines 52-54.	21
Y	US, A, 3,783,502 (RICHTER ET AL) 08 January 1974, col. 8, lines 53-59.	
Y	US, A, 4,928,027 (DEININGER ET AL.) 22 May 1990, col. 4, lines 10-19.	25